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STRUCTURAL DESIGN AND TEST FACTORS OF SAFETY FOR SPACEFLIGHT HARDWARE

MEASUREMENT SYSTEM IDENTIFICATION:
INCH-POUND/METRIC

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This document represents the technical consensus of the developing group but does not yet have final NASA approval.

DOCUMENT HISTORY LOG

Status	Document Revision	Approval Date	Description
Baseline		6-21-1996	Baseline Release
Interim Revision	A	09-12-2006	General: Changed to conform to standard template. FOREWORD: Updated to indicate why Revision A is necessary: Added: “Revision A of this standard incorporates additional design and qualification requirements for pressure vessels, pressurized structures, pressurized components, and structural softgoods, along with updates to minimum design factors for joint separation of preloaded joints.” 1.2 Applicability. Added sentence: “NASA programs and projects that do not meet the provisions of this document shall be assessed by the NASA Program Manager for the associated risk to the success of the planned NASA mission and approved by the assigned Technical Authority.” Also in last paragraph: Deleted “pressure vessels, pressurized components,”. APPLICABLE DOCUMENTS: Added two Applicable Documents: ANSI/AIAA S-080 and ANSI/AIAA S-081. 2.4 Added Order of Precedence 3.1 Added Acronyms Section 3.2. Added two definitions: pressurized structures and structural

			softgoods. Removed definition numbering. Section 4.1.2.1. Added “, especially if the test or the test article is nonlinear. Strength model verification may not be required if the load path and the flight loads are straightforward and easy to understand. (Approval from the responsible Technical Authority shall be required.) Section 4.1.2.3, 1st paragraph. Added “For metallic structures only, …” Section 4.1.2.3, last paragraph. Deleted “Standard criteria cannot be specified for general use in designing structures for which no verification tests are planned.” Changed from “... responsible NASA Center” to “...appropriate Technical Authority.” Deleted “For spacecraft and other payloads launched on the Space Shuttle, these criteria must also be approved by the Space Shuttle Payload Safety Review panel prior to their implementation. Changed table numbering from I-V to 1-5. Section 5.1.2: Deleted “In both cases, the preload plus induced fastener loads times the factor of safety shall be less than the fastener ultimate strength.” Table 2. Changed NOTE from: “Joints that maintain pressures and/or hazardous materials in a safety-critical application,” to

			“Joints where structural failure could cause a catastrophic event.” Defined “discontinuity” with a note in table 3. Table 4. Changed the acceptance or proof load factor for protoflight nonpressurized from 1.2 to 3.0 and pressurized from 2.0 to 3.0 and added two notes. This will make NASA-STD-5001 consistent with an in-process NASA Standard for glass, ceramics, and windows. Table 5. Changed the table from 1.2 to 3.0 proof test factor for qualification and acceptance. Also added the note to the table. Deleted Qualification Test Factor column. Added 5.1.6 Pressure Vessels, Pressurized Structures, and Pressurized Components. Pressure vessels and pressurized vessels, pressurized structures, and pressurized components shall be designed and qualified per the requirements of ANSI/AIAA S-080 (metals) and ANSI/AIAA S-081 (composites). All relevant load combinations are applicable. Added Section 5.1.7 Factors of Safety for Softgood Structures. Static Strength of all structural softgoods shall be test verified. The minimum design and test factors of safety for structural softgoods shall be as specified in table 6. Added table 6, Minimum Design and Test Factors for Structural Softgoods. Section 5.3. Added sentence, “If the lower factors of safety are approved

			by the responsible NASA Center, a waiver shall be written that documents the rationale for this one-time exception. This waiver shall not be used as a precedent for future mission applications.”

FOREWORD

This Interim Technical Standard is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item. Use of this standard is the responsibility of the user.

This standard is approved for use by NASA Headquarters and NASA Centers, including Component Facilities.

The material covered in this standard is based on the consensus judgment of a working group of structural engineers from all the NASA Centers. The group was empowered by the NASA Engineering Management Council (EMC) to develop more uniform design and verification criteria to be applicable NASA wide. This activity was prompted by concerns expressed by industry and NASA program management that practices and requirements in this area vary widely between Centers, making the verification of structural adequacy difficult in cases involving multiple Centers, and increasing costs to verify identical hardware under different criteria.

Revision A of this standard incorporates additional design and qualification requirements for pressure vessels, pressurized structure, pressurized components, and structural softgoods, along with updates to minimum design factors for joint separation of preloaded joints.

Requests for information, corrections, or additions to this standard should be submitted via "Feedback" in the NASA Technical Standards System at http://standards.nasa.gov.

Original signed by:

	09-12-06
Christopher J. Scolese NASA Chief Engineer	Approval Date

TABLE OF CONTENTS

TABLE OF CONTENTS, continued

LIST OF TABLES

This document represents the technical consensus of the developing group but does not yet have final NASA approval.

Structural Design and Test Factors of Safety for Spaceflight Hardware

1. SCOPE

1.1 Purpose

The purpose of this standard is to establish structural strength design and test factors, as well as service life factors to be used for spaceflight hardware development and verification. It is intended to reduce space project costs and schedules by enhancing the commonalty of use of hardware designs between NASA flight projects, Centers, and their contractors. While it is true that structural designs are sometimes governed by criteria other than strength, the criteria in this document are to be considered as minimum acceptable values unless adequate engineering risk assessment is provided which justifies the use of lower values.

1.2 Applicability

This standard recommends engineering practices for NASA programs and projects. It may be cited in contract, program, and other Agency documents as a technical requirement or as a reference for guidance. Except where noted as mandatory, individual provisions of this standard may be tailored (i.e., modified or deleted) by contract or program specifications to meet specific program/project needs and constraints. Tailoring must be formally documented as part of program/project requirements and approved by the assigned Technical Authority.

Determining the suitability of this standard and its provisions is the responsibility of program/project management and the performing organization. Project-specific tailoring may generate other project specific requirements that are derivatives of this standard. NASA Programs and projects that do not meet the provisions of this document shall be assessed by the NASA Program Manager for the associated risk to the success of the planned NASA mission and approved by the assigned Technical Authority. This document shall not supersede applicable laws and regulations unless a specific exemption has been obtained.

The criteria in this standard are applicable to launch vehicles, including their propellant tanks and solid rocket motor cases, and payloads. These criteria apply to flight hardware which is utilized for NASA missions. The standard presents acceptable minimum factors of safety for use in analytical assessment and test verification of structural adequacy of the flight hardware. Designs must generally be verified by both structural strength analyses and tests. The factors are to be multiplied by the limit stresses (including additive thermal stresses), and the products must be verified not to exceed material allowable stresses (yield and ultimate) under the expected temperatures and other operating conditions.

Criteria are specified for design and test of flight articles where the actual flight hardware is tested (protoflight), and where qualification tests are conducted on a separate (prototype) article. In general, no distinction is made between “manned” and “unmanned” missions. Structures of manned flight systems may be subjected to additional verification and/or safety requirements (e.g., fracture control) that are consistent with the established risk levels for mission success and flight crew safety.

The requirements specifically excluded from this standard are design loads determination, fracture control, engines, rotating hardware, solid propellant, insulation, ground support equipment, and facilities. Also excluded are specific configuration factors, such as fitting factors, buckling knockdown factors, and load uncertainty factors.

1.3 Constraints and Preconditions

The criteria of this standard were developed in the context of structural and mechanical systems designs which are amenable to engineering analyses by current state-of-the-art methods and conforming to standard aerospace industry practices. More specifically, the designs are assumed to use materials having mechanical properties that are well characterized for the intended service environments and all design conditions. For reusable and multi-mission hardware, these criteria are applicable throughout the design service life and all of the missions. Therefore, design considerations must include material property degradation under the service environments. Material allowables shall be chosen to minimize the probability of structural failure due to material variability. Allowables shall be based on sufficient material tests to establish values on a statistical basis. Further, the service environments and limit loads shall be well defined, and aerospace standard manufacturing and process controls shall be used in the hardware fabrication and handling. Test hardware shall be representative of the flight configuration.

2. APPLICABLE DOCUMENTS

2.1 General

The documents listed in this section contain provisions that constitute requirements of this standard as cited in the text of section 4. The latest issuances of cited documents shall be used unless otherwise approved by the assigned Technical Authority. The applicable documents are accessible via the NASA Technical Standards System at http://standards.nasa.gov, directly from the Standards Developing Organizations (SDOs), or other document distributors.

2.2 Government Documents

None.

2.3 Non-Government Documents

ANSI/AIAA S-080	Space Systems – Metallic Pressure Vessels, Pressurized Structures, and Pressurized Components
ANSI/AIAA S-081	Space Systems – Composite Overwrapped Pressure Vessels (COPVs)

2.4 Order of Precedence

In the case of conflict, the requirements in the Applicable Documents section have least precedence.

3. ACRONYMS AND DEFINITIONS

3.1. Acronyms

COPVS	Composite Overwrapped Pressure Vessels
EMC	Engineering Management Council
MDP	Maximum Design Pressure
NASA	National Aeronautics and Space Administration
psia	pounds per square inch absolute
SDO	Standards Developing Organization
SRM	solid rocket motor

3.2 Definitions

Acceptance Test: A test performed on each article of the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, acceptance, proof, and protoflight tests are synonymous.

Creep: Time-dependent permanent deformation under sustained load and environmental conditions.

Detrimental Yielding: Yielding that adversely affects the fit, form, function, or integrity of the structure.

Factors of Safety (Safety Factors): Multiplying factors to be applied to limit loads or stresses for purposes of analytical assessment (design factors) or test verification (test factors) of design adequacy in strength or stability.

Failure: Rupture, collapse, excessive deformation, or any other phenomenon resulting in the inability of a structure to sustain specified loads, pressures, and environments, or to function as designed.

Fatigue: The cumulative irreversible damage incurred in materials caused by cyclic application of stresses and environments resulting in degradation of load carrying capability.

Limit Load: The maximum anticipated load, or combination of loads, which a structure may experience during its service life under all expected conditions of operation or use.

Maximum Design Pressure (MDP): The highest possible operating pressure considering maximum temperature, maximum relief pressure, maximum regulator pressure, and, where applicable, transient pressure excursions. MDP for Space Shuttle payloads is a two-failure tolerant pressure; i.e., will accommodate any combination of two credible failures that will affect pressure during association with the Space Shuttle. MDP also accommodates the maximum temperature to be experienced in the event of an abort to a site without cooling facilities.

Pressure Vessel: A container designed primarily for storing pressurized gases or liquids and (1) contains stored energy of 14,240 foot-pounds (19,309 Joules) or greater, based on adiabatic expansion of a perfect gas; or (2) experiences a limit pressure greater than 100 psia (689.5 kiloPascal [kPa] absolute); or (3) contains a pressurized fluid in excess of 15 psia (103.4 kPa absolute), which will create a safety hazard if released.

Pressurized Component: A line, fitting, valve, or other part designed to contain pressure and that (1) is not made of glass, or (2) is not a pressure vessel, or (3) is not a propellant tank, or (4) is not a solid rocket motor (SRM) case.

Pressurized Structures: Structures designed to carry both internal pressure loads and vehicle structural loads. The main propellant tank of a launch vehicle is a typical example.

Proof Test: A test performed on the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, proof, acceptance, and protoflight tests are synonymous.

Proof Test Factor: A multiplying factor to be applied to the limit load or MDP to define the proof test load or pressure.

Protoflight Test: A test performed on the flight hardware to verify workmanship, material quality, and structural integrity of the design. In the protoflight structural verification approach, protoflight, acceptance, and proof tests are synonymous.

Prototype Test: A test performed on a separate flight-like structural test article to verify structural integrity of the design. Prototype tests and qualification tests are synonymous.

Qualification Test: A test performed on a separate flight-like structural article of each type to verify structural integrity of the design. Qualification and prototype tests are synonymous.

Qualification Test Factor: A multiplying factor to be applied to the limit load or MDP to define the qualification test load or pressure.

Safety Critical: A classification for structures, components, procedures, etc., whose failure to perform as designed or produce the intended results would pose a threat of serious personal injury or loss of life.

Service Life: All significant loading cycles or events during the period beginning with manufacture of a component and ending with completion of its specified use. Testing, transportation, lift-off, ascent, on-orbit operations, descent, landing and post-landing events shall be considered.

Service Life Factor (Life Factor): A multiplying factor to be applied to the maximum expected number of load cycles in the service life to determine the design adequacy in fatigue or fracture.

Structural Softgoods: Straps, fabrics, inflatable structures, gossamer structures and others that carry structural loads upon launch or deployment.

Ultimate Design Load: The product of the ultimate factor of safety and the limit load.

Ultimate Strength: The maximum load or stress that a structure or material can withstand without incurring failure.

Yield Design Load: The product of the yield factor of safety and the limit load.

Yield Strength: The maximum load or stress that a structure or material can withstand without incurring detrimental yielding.

4. GENERAL REQUIREMENTS

4.1 Selection Criteria for Factors of Safety

The appropriate design and test factors for a given mechanical or structural flight hardware element depend on several parameters such as the materials used, attachment methods (e.g., bonding), and the verification approach (prototype or protoflight). In applying the minimum factors of safety specified in this standard, it must be recognized that some structural and mechanical members and systems may be required to meet other more stringent and restrictive performance requirements such as dimensional stability, pointing accuracy, stiffness/frequency constraints, or safety requirements (e.g., fracture control).

4.1.1 Prototype versus Protoflight Approaches

The standard accepted practice for verification of launch vehicles is the prototype approach in which a separate, dedicated test structure, identical to the flight structure, is tested to demonstrate that the design meets the factor of safety requirements.

A widely used acceptable alternative for verification of spacecraft and science payloads is the protoflight approach, wherein the flight structure is tested to levels somewhat above limit stress (or load) but below yield strength. In order to preclude detrimental yielding during protoflight strength verification testing, the yield factor of safety for protoflight structural design must be higher than the test factor. The protoflight test shall be followed by inspection and functionality assessment.

Consideration shall be given to development test prior to committing to major test article configurations and especially prior to committing the flight article to protoflight test.

4.1.2 Test Verification Criteria

4.1.2.1 Test Methods

Strength verification tests fall into three basic categories: (1) tests to verify strength of the design (qualification, acceptance, or proof); (2) tests to verify strength models; and (3) tests to verify workmanship and material quality of flight articles (acceptance or proof).

Strength verification tests are normally static load tests covering all critical load conditions in the three orthogonal axes and, generally, can be classified as prototype or protoflight (see 4.1.1). The magnitude of the static test loads should be equivalent to limit loads multiplied by the qualification, acceptance, or proof test factor. In some cases, alternative test approaches (centrifuge, below resonance sine burst, saw tooth shock, etc.) are more effective in reproducing the critical load or environmental conditions and may be used in lieu of static testing if it can be demonstrated that the resulting loads in the test article are equivalent to or larger than the limit loads multiplied by the test factor.

Strength model verification tests are normally done as part of the strength verification. Model verification must be accomplished over the entire load range, especially if the test or the test article is nonlinear. Strength model verification may not be required if the load path and the flight loads are straight forward and easy to understand. (Approval from the responsible Technical Authority shall be required.) The test article must be adequately instrumented to provide sufficient test data for correlation with the strength model. Workmanship tests may be static or dynamic load tests. Dynamic tests may be sinusoidal vibration, random vibration, or acoustic. Test loads should be equivalent to or slightly higher than the limit loads. Each propellant tank and each solid rocket motor case shall be proof pressure tested.

4.1.2.2 Test versus Design Factors of Safety

When using the prototype structural verification approach, the minimum ultimate design factors can be the same as the required qualification test factors for both metallic and composite/bonded structures. Metallic structures should be verified to have no detrimental yielding at yield design load before testing to full qualification load levels.

When using the protoflight structural verification approach, design factors larger than the required acceptance or proof test factors shall be used to prevent detrimental yielding of the metallic or damage to the composite/bonded flight structure during test.

4.1.2.3 Test versus No-test Options

Structural designs generally should be verified by analysis and by either prototype or protoflight strength testing. For metallic structures only, it may be permissible to verify structural integrity by analysis alone without strength testing, provided an acceptable engineering rationale is developed. Increasing the design factors of safety does not by itself justify this “no-test” approach. Some examples of criteria on which to base such an approach are as follows:

a. The structural design is simple (e.g., statically determinate) with easily determined load paths; it has been thoroughly analyzed for all critical load conditions; and there is a high confidence in the magnitude of all significant loading events.

b. The structure is similar in overall configuration, design detail, and critical load conditions to a previous structure which was successfully test verified, with good correlation of test results to analytical predictions.

c. Development and/or component tests have been successfully completed on critical, difficult to analyze elements of the structure. Good analytical model correlation to test results has been demonstrated.

Projects which propose to use the “no-test” approach generally must use larger factors of safety and develop project specific criteria and rationale for review and approval by the appropriate Technical Authority.

4.1.3 Probabilistic Methods

Design factors of safety and test factors are intended to conservatively compensate for uncertainties in the strength analysis. Current standard NASA structural verification criteria are deterministic, and experience has shown these deterministic criteria to be adequate. The probabilistic method uses knowledge (or assumptions) of the statistical variability of the design variables to select design criteria for achieving an overall success confidence level. Any proposed use of probabilistic criteria to supplement deterministic factors of safety shall be approved by the responsible NASA Center on an individual case basis.

5. DETAILED REQUIREMENTS

5.1 Design and Test Factors of Safety

The design factors of safety and test factors of this standard are the minimum required values for NASA spaceflight structures and shall be applied to both mechanical and additive thermal stresses. Applications of these factors to the development and verification of a structure will be accepted by the responsible NASA Center only when all of the constraints and preconditions specified in 1.3 are met. Higher factors than those listed here may be required for proof testing if the proof test is to be used for fracture control flaw screening. If pressure or temperature has a relieving or stabilizing effect on the mode of failure, then for analysis or test of that failure mode, the unfactored stresses induced by temperature or the minimum expected pressure shall be used in conjunction with the ultimate (factored) stresses from all other loads. Otherwise, the design and test factors shall be applied equally to MDP and other stresses.

Factors of safety on yield are not specified for fasteners, composite/bonded structures, glass, and bonds for structural glass. These hardware items shall be designed to preclude any detrimental permanent deformation or functional degradation of the flight system under the limit loads and, for programs employing the protoflight verification approach, the acceptance or proof test loads.

5.1.1 Metallic Structures

Spaceflight metallic structures can be developed using either the prototype or the protoflight approach. The minimum design and test factors of safety for metallic structures, excluding fasteners, are specified in table 1.

Table 1—Minimum Design and Test Factors for Metallic Structures

Verification Approach	Ultimate Design Factor	Yield Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	1.4	1.0*	1.4	NA or 1.05**
Protoflight	1.4	1.25	NA	1.2

NOTES:
* Structure must be assessed to prevent detrimental yielding during flight, acceptance, or proof testing.
** Propellant tanks and solid rocket motor cases only.

5.1.2 Fasteners and Preloaded Joints

The minimum design and test factors for fasteners shall be as specified in table 2. The strength of fasteners used in preloaded joints shall be assessed at zero and maximum preload. For the zero preload case, the factor of safety shall be applied to the induced fastener load. For the maximum preload case, the factor of safety need only be applied to the additional fastener load induced beyond the preload. Unless specifically designed to separate, all joints shall maintain the factor of safety in table 2 against separation. Minimum preload shall be used in the separation assessment.

Table 2—Minimum Design and Test Factors for Fasteners and Preloaded Joints

Verification Approach	Design Factors			Test Factors	
	Ultimate Strength	Joint Separation		Qualification	Acceptance or Proof
		Safety Critical*	Other		
Prototype	1.4	1.4	1.2	1.4	NA
Protoflight	1.4	1.4	1.2	NA	1.2

NOTE:
* Joints where structural failure could cause a catastrophic event.

5.1.3 Composite/Bonded Structures

Composite/bonded structures, excluding glass, developed for NASA spaceflight missions shall, as a minimum, use the design and test factors specified in table 3. Each flight article under the composite/bonded prototype approach requires acceptance or proof testing unless the requirements of 4.1.2.3 or 5.3 are met.

Table 3—Minimum Design and Test Factors for Composite/Bonded Structures

Verification Approach	Geometry of Structure	Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	Discontinuities**	2.0*	1.4	1.05
	Uniform Material	1.4	1.4	1.05
Protoflight	Discontinuities**	2.0*	NA	1.2
	Uniform Material	1.5	NA	1.2

NOTE:
* Factor applies to concentrated stresses. For non-safety critical applications, this factor may be reduced to 1.4 for prototype structures and 1.5 for protoflight structures.
** Discontinuities are defined as an interruption in the physical structure or configuration of the part. Delaminations, debonds, and dropping of plies are all assumed to be discontinuities.

5.1.4 Glass

The minimum design and test factors for pressurized and nonpressurized glass shall be as specified in table 4. The structural integrity of all pressurized glass components shall be verified by both analysis and test. Nonpressurized glass may be verified by analysis only with an ultimate minimum design factor of safety of 5.0. A dedicated test article shall be developed and subjected to qualification testing. Each subsequent flight unit shall be subjected to acceptance proof testing. The qualification test article may be refurbished and reproof tested to establish the minimum required structural integrity for flight, although this approach involves increased risk due to the additional testing and handling of the hardware. Testing shall be configured to simulate flight-like boundary conditions and loading. For acceptance testing, the total time during load, dwell, and unload shall be as short as possible and shall be done in an inert environment to minimize flaw growth. Care should also be taken to configure flight hardware to prevent overloading any bonded joints during test. The test verification approach, including any plan to refurbish and retest qualification hardware in order to upgrade to flight status, shall be coordinated with the responsible technical authority for review and approval.

This document represents the technical consensus of the developing group but does not yet have final NASA approval.

Table 4 – Minimum Design and Test Factors of Safety for Glass

Verification Approach	Loading Condition	Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor*
Test	**Nonpressurized****	**3.0**	**3.0**	**3.0**
	Pressurized	**3.0**	**3.0**	**3.0**
Analysis Only	**Nonpressurized**	**5.0**	**NA**	**NA**

*** Glass shall be proofed tested to 3.0 times design limit load. This proof test then establishes the ultimate strength allowable of this glass component.**

**** Nonpressurized glass equals nonstructural.**

5.1.5 Bonds for Structural Glass

Bonds for structural glass shall be qualification tested on a separate article, and each flight article shall be proof tested. The design and test factors are specified in table 5.

Table 5—Minimum Design and Test Factors for Structural Glass Bonds

Ultimate Design Factor	Acceptance or Proof Test Factor*
3.0	3.0

* Structural glass bonds shall be proofed tested to 3.0 times design limit load. This proof test then establishes the ultimate strength allowable of this glass component.

5.1.6 Pressure Vessels, Pressurized Structures, and Pressurized Components

Pressure vessels and pressurized vessels, pressurized structures, and pressurized components shall be designed and qualified per the requirements of ANSI/AIAA S-80 (metals) and ANSI/AIAA S-81 (composites). All relevant load combinations are applicable.

5.1.7 Factors of Safety for Softgood Structures

Static strength of all structural softgoods shall be test verified. The minimum design and test factors of safety for structural softgoods shall be as specified in table 6.

Table 6 – Minimum Design and Test Factors for Structural Softgoods

Safety Criticality Classification	Ultimate Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
1 or 2	**4.0**	**4.0**	**1.2**
3	**2.0**	**2.0**	**1.2**

5.2 Fatigue and Creep

For NASA spaceflight structures made of well-characterized materials and with sufficient load cycle data that accounts for all in-service environments, a minimum service life factor of 4.0 shall be applied to the service life for fatigue and creep-life assessments.

5.3 Alternate Approaches

In the event a particular factor of safety requirement of this standard cannot be met for a specific spaceflight structure or hardware component, an alternative or modified approach shall be proposed to verify the strength adequacy of the design. A written risk assessment that justifies the use of the alternate approach must be prepared by the organization with primary responsibility for the development of the structure or component. The risk assessment shall be submitted to the responsible NASA Center for approval prior to the implementation of the alternative approach. If the lower factors of safety are approved by the responsible NASA Center, a waiver shall be written that documents the rationale for this one-time exception. This waiver shall not be used as a precedent for future mission applications.

6. GUIDANCE

6.1 Key Word Listing

Acceptance test
Factors of safety
Proof test
Protoflight test
Prototype test
Qualification test
Spaceflight hardware
Standard
Structural design criteria
Test factors
Verification